

# REPORT DOCUMENTATION PAGE

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<b>14. ABSTRACT</b> We have completed a thorough study of maser action of hyperpolarized He-3 gas in inhomogeneous magnetic fields. The self interaction of the He-3 magnetization has a large effect on the maser gain. We have developed a simple new magnetic resonance method for investigating the interactions of Xe-129 spins with protons in polymers. We have shown that there are novel magnetic resonance transitions in alkali-metal vapors that have vanishing spin-exchange broadening in the limit of high spin polarization. Such transitions could be useful for miniaturized atomic clocks. We have shown that spin-axis interactions in triplet molecules are responsible for much of the spin destruction rate dense alkali-metal vapors.					
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**ANNUAL REPORT**  
For the Research Period  
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for work performed under

**Grant AFOSR F49620-98-1-0127**

**PHYSICS UTILIZING SPIN POLARIZED GASES.**

Submitted August 8, 2002

by

William Happer, Co-Principal Investigator

## **1. Overview**

The research supported by this grant was focused on the fundamental physics and applications of spin polarized atoms. One of the most unexpected applications of this work has been in medical imaging of human lungs with laser-polarized  $^3\text{He}$  and  $^{129}\text{Xe}$  gas. Basic research, supported by AFOSR in our group, eventually led to ways to produce liter-atmospheres of  $^3\text{He}$  and  $^{129}\text{Xe}$  gases with spin polarizations of many tens of percent, instead of the parts per million that is normal for magnetic resonance imaging. When inhaled these gases give spectacular images of human lungs, sinuses and other air passages. There is a vigorous clinical center for lung imaging with hyperpolarized gases at the University of Virginia in Charlottesville. That work is sponsored by the international health care company, Nycomed Amersham, which purchased Magnetic Imaging Technologies, Inc., a start up company formed a few years ago to commercialize this AFOSR technology. One of the most interesting gas-imaging activities underway now is a long-term study of the lungs of New York City firemen who survived the collapse of the World Trade Center towers on September 11, 2001.

The work supported by this AFOSR grant has had and will continue to have applications to many technologies of the United States Air Force. For example, the Rb clocks used in the GPS satellite system are based on optical pumped gas cells. The basic physical processes operating in these clocks is closely related to that of the cells used to polarize  $^3\text{He}$  and  $^{129}\text{Xe}$  gas for medical imaging. During the research period covered by this report, we accidentally discovered that there are certain novel magnetic resonance transitions, suitable for use in atomic clocks, that are almost unaffected by the spin-exchange broadening that affects the traditional 0-0 clock transition.

Much of the work supported by this grant has already been published in peer-reviewed journals, as listed below, but we will give a brief summary of some of the more important accomplishments in the next section.

## **2. Major Accomplishments**

**Spin Masers.** The spin polarization of hyperpolarized gas can be so high that the spins can couple enough negative resistance into a nearby resonant circuit to allow spontaneous oscillation or masing. In work led by Dr. Michael Romalis, we have completed an experimental and theoretical investigation of the masing of hyperpolarized  $^3\text{He}$  gas in

solenoidal coils. The masing can be suppressed by intentionally making the magnetic field inhomogeneous. The masing can be enhanced when atoms near either end of the cylinder are in resonance, since the end walls of the cylinder suppress the diffusional damping of the precessing magnetization. Because of the unusually large spin polarization, the self-fields of the spins can be comparable to the fields due to current oscillating in the coils. We were able to quantitatively understand these unusual maser systems with a theory based on an expansion of the precessing magnetization in a series of Airy functions.

**Surface relaxation.** Xenon atoms readily dissolve in polymer surface coatings, the walls of polymer tubing and other organic media. The large density of protons in such materials often leads to very rapid spin relaxation of  $^{129}\text{Xe}$  atoms. In work led by Karen Sauer and Richard Fitzgerald, we have developed a simple, new resonance method to study the interactions of  $^{129}\text{Xe}$  nuclei with protons in organic materials. Unlike earlier methods that made use of "Hartmann-Hahn" matching of the nuclear Larmor frequencies in two rotating magnetic fields, only one rotating field is needed for this method, so it is much easier to use.

**Comprehensive Theory of Spin Exchange Optical Pumping.** A comprehensive theoretical analysis of the key physics of spin-exchange optical pumping has been completed and published. The most important spin relaxation mechanisms of ground-state and excited-state alkali-metal atoms are included, as well as the details of the optical pumping process and the effects of radiofrequency fields. This theory has been invaluable for analysis of many new and important phenomena involving the production of hyperpolarized gases and the issues involved in miniaturizing atomic clocks.

**Spin-Exchange Narrowing of Magnetic Resonance Lines.** Spin-exchange collisions are one of the major relaxation mechanisms for spin-polarized alkali-metal atoms. Spin-exchange collisions conserve the total spin-polarization of the colliding atoms, but they can "reshuffle" the sublevels in which the atoms find themselves before and after a collision. This reshuffling normally leads to a broadening of the linewidths of magnetic resonance transitions that is proportional to the spin-exchange rate. The spin-exchange broadening is perhaps the most fundamental reason that it has been so hard to make miniaturized atomic clocks, since the more crowded atoms in a miniaturized clock have faster spin-exchange rates. A surprising result of work supported by this AFOSR grant has been the discovery of several special transitions for which the spin-exchange broadening vanishes in the limit of high spin polarization. These "end transitions" connect the sublevels of maximum or minimum spin angular momentum to sublevels with one less unit of angular momentum. Because of the high angular momentum of the oscillating atoms, the collisions, which have to conserve angular momentum, cannot knock the atoms out of their initial states, since the final states all have less angular momentum. We have shown experimentally that for high vapor densities, where spin-exchange collisions are the dominant contribution to the line width, increasing the optical pumping power from the laser causes a substantial narrowing of the line widths of the end transitions. The observations are in excellent agreement with theoretical expectations. By exploiting this unexpected property of end transitions, we may be able to make much smaller atomic clocks.

**Relaxation Due to Spin-Axis Interactions in Alkali-Metal Vapors.** Spin-exchange is the most important result of collisions between alkali-metal atoms, but in a

small fraction of the collisions some spin angular momentum is converted into translational angular momentum. We call these rare collisions, *spin-destruction* collisions to distinguish them from spin-exchange collisions. The spin-destruction rates can be as much as 1% of the spin-exchange rates for Cs-Cs collisions, but they are a smaller fraction for Rb-Rb collisions and an even smaller fraction for K-K collisions. In work led by Chris Erickson in collaboration with colleagues at the University of Wisconsin, we have shown conclusively that a major part of the spin-destruction rate is due to a spin-axis interaction which occurs for triplet states of the colliding pair. The spin-axis interaction was identified without the ambiguity that often bedevils relaxation rate experiments, since we were able to observe unique resonances in the magnetic decoupling curve of the relaxation rates.

### 3. Publications

Activities receiving full or partial support from Grant AFOSR F49620-98-1-0127 have resulted in the 5 refereed publication listed below, and also several abstracts, contributed and invited talks at scientific conferences.

S. Appelt, A. Ben-Amar Baranga, A. R. Young, and W. Happer, "Light Narrowing of Rubidium Magnetic Resonance Lines in High-Pressure Optical-Pumping Cells," Phys. Rev. A **59**, 1 (1999).

M. K. L. Sauer, R. J. Fitzgerald, and W. Happer, "Resonance Technique to Probe  $^{129}\text{Xe}$  Surface Interactions," Phys. Rev. A **59**, R1746 (1999).

R. J. Fitzgerald, M. Gatzke, David C. Fox, G. D. Cates, and W. Happer, " $^{129}\text{Xe}$  Spin Relaxation in Frozen Xenon," Phys. Rev. B, **59**, 8795 (1999).

M. Romalis and W. Happer, "Inhomogeneously Broadened Spin Masers," Phys. Rev. A **60**, 1385 (1999).

C. J. Erickson, D. Levron, S. Kadlecik, B. Chann, L. W. Anderson, T. G. Walker and W. Happer, "Spin Relaxation Resonances Due to the Spin-Axis Interaction in Dense Rubidium and Cesium Vapor," Phys. Rev. Letters **85**, 4237 (2000).

### 4. Personnel

The following personnel received full or partial support from Grant AFOSR F49620-94-1-0466:

Dr. William Happer, Co-Principal Investigator.

Dr. Gordon Cates, Co-Principal Investigator.

Dr. Michael Romalis, Assistant Professor.

Dr. David Levron, Visiting Research Scientist.

Dr. Andrei Baranga, Visiting Research Scientist.

Dr. Stephan Appelt, Research Associate

Dr. Richard Fitzgerald, Research Associate.

Mr. Dan Walter, Graduate Student, PhD candidate.

Ms. Karen Sauer, Graduate Student, PhD candidate.

Mr. Christopher Erickson, Graduate Student, PhD candidate.

Mr. David C. Fox, Undergraduate Senior Thesis Student.